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14. ABSTRACT
The University of Cincinnati partnered with SRI and the University of Washington (UW) to develop and validate robotic technology that enables telesurgical and autonomous robotic therapeutics. This surgical robotics research was conducted in part in the National Undersea Research Center (NURC) Aquarius Habitat during the NASA Extreme Environment Mission Operations (NEEMO) 12. Two robotic systems, SRI's M7 and the UW's RAVEN, were modified with updated hardware/software and were deployed to the habitat for evaluation. This research represents an important step in the evolution of surgical robotics from telesurgery to distributed autonomous therapeutics that includes remote supervisory-controlled, semi-autonomous robotic function. This research marked the first time ever that a surgeon, remotely located from the robotic system and simulated tissue, was able to insert a needle into a blood vessel using ultrasound-image guidance. More importantly, the robotic system was able to autonomously insert a needle into a simulated blood vessel. Further distributed autonomous therapeutics research is indicated to help save the lives and limbs of our injured warfighters.

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NEEMO 12, Telesurgery, Robotic Surgery, Military Medicine, Extreme Environments, Semi-Autonomous Function

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PI Charles R. Doarn, MBA

UNIVERSITY OF Cincinnati

Center for Surgical Innovation

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INTRODUCTION

In recent years, the U.S. Army's Telemedicine and Advanced Technology Research Center (TATRC) has been a strategic partner, providing funding for research initiatives and activities in telesurgery. These successive research initiatives have evolved from telementoring to telesurgery to semi-autonomous function of key medical tasks.

The ability to place surgical robotics that can be manipulated remotely and perform semi-autonomous functions can add tremendous value to military medicine by providing surgical care more immediately. In addition, the ability to remotely perform medical tasks like needle insertion through semi-autonomous supervisory control can lead to new approaches in delivery of care for the warfighters.

The purpose of this TATRC-funded research was to conduct collaborative accelerated medical technology development through the evaluation of two different robotic (telemanipulation) surgical systems – SRI's M7 and University of Washington's (UW) RAVEN in an extreme environment, using a telecommunications link. The focus of this research was to explore techniques and develop technologies necessary to make telesurgery and telerobotic supervisory autonomous function more "effective" and relevant in everyday surgical practice as well as in provision of life and limb saving emergency surgery to an injured soldier in the battlefield. This program also sought to answer a fundamental question related to the ability to remotely control a robot outfitted with an ultrasound to permit a remote surgeon to semi-autonomously insert a needle into a simulated blood vessel. This was successfully accomplished with the M7.

This TATRC-funded research supported (1) the development and reconfiguration of both robotic systems so that they could be deployed in an extreme environment; (2) the development of a semi-autonomous (supervisory) capability of a key medical task; (3) evaluation of the semi-autonomous task in an extreme environment; and (4) evaluation of basic surgical task using a standardized surgical training system.

This research was very successful. Both robots were deployed and evaluated. The semi-autonomous function of the M7 was highlighted during the American Telemedicine Association (ATA) annual meeting in Nashville, TN. The results of the TATRC-funded telesurgery research highlight the ongoing collaboration between various organizations, continuing the development of telesurgical autonomous robotics as a significant tool for healthcare delivery in extreme environments, especially for future application in medical care of the warfighter. Data analysis of the research data is underway.

This document serves as the final report of this telesurgery research.

TELESURGERY BACKGROUND

The state of telesurgery, those activities that have been performed during the past several years, is the direct result of TATRC's involvement. Each TATRC-funded activity has led a progressive chronology of telementoring to telesurgery to semi-autonomous function. The aim of this research has been to push the development of surgical robotics to provide expert care to injured warfighters on the battlefield; incorporating telecommunications capabilities and semi-autonomous functions. Through effective and collaborative partnerships with the UC, SRI, and UW, and a series of research initiatives - NEEMO 7, NEEMO 9, High Altitude and Platforms for Mobile Robotic Telesurgery (HAPsMRT) - this evolution has transpired. This research has indicated that there are communications constraints and that some level of autonomy is required.

Telesurgery research focuses on evaluation and accelerated development of robotic and telecommunication systems required for robust telesurgery application. TATRC funding has been previously targeted toward most telesurgery activities that have occurred and which the assembled team at UC has been involved in. These efforts include two previous NEEMO missions (NEEMO 7 and NEEMO 9), the da Vinci telesurgery activities (led by Intuitive Surgical), and the UC-led HAPsMRT. Several of these projects required the use of robotics systems or telemanipulation systems used in surgical care. The SRI M7 and the UW RAVEN are the two, which have seen significant investment and evaluation in telesurgery experiments.

SRI, International M7

In 1996, SRI, working with DARPA, advanced the state-of-the-art of telepresence and telemanipulation when it designed and prototyped the M7 series of telerobotic manipulators. This haptics-enabled master-slave system featured an anthropomorphic scale, a large 40 cm on-a-side workspace, and high-resolution stereoscopic video cameras and displays. Featuring seven haptic-capable degrees of freedom (including grip), and interchangeable surgical instruments, it was the first telepresence and telemanipulation system specifically designed for performing open trauma surgical procedures. SRI was also the developer of the da Vinci robotic platform now commercialized through Intuitive Surgical.

Since the summer of 2005, SRI has worked to extend its telerobotic platform for field testing in extreme environments. SRI (1) invested internal research and development funds to upgrade the M7 platform to have separate master and slave electronics, (2) wrote software to permit teleoperation over Internet Protocol (IP), (3) reduced the size and weight of the system, and (4) ruggedized the control electronics. Spinning disks within the system been replaced with solid state flash memory to permit operation in harsh environments.

In December 2005, SRI conducted a series of long-distance teleoperation tests between SRI's Menlo Park, CA and Ontario, Canada, to tune the performance of the robot, and identify areas for improvement of software and hardware required to meet identified mission objectives. In April 2006, it was successfully deployed in the NURC Aquarius habitat as part of the TATRC-funded NEEMO 9. This was the first time a surgical robot had been used to perform simulated surgery in such a small and harsh environment. Dr. Mehran Anvari, located in Hamilton, Ontario, Canada, successfully sutured simulated skin located in the habitat despite an introduced latency of over two seconds. Dr. Broderick, NEEMO 9 crewmember, served as a key researcher in the Aquarius habitat during this mission. A two second latency impacts a single suture placement, resulting in a single knot tying taking ten minutes to accomplish.

This system, used in NEEMO 9 could not support clinical use due to the communication limitations and latency. Therefore, it became apparent that semi-autonomous function could help ameliorate these issues. This required further development of semi-autonomous capabilities. Although short term solutions will emerge, research must be continued.

Issues of communications and latency require novel approaches and solutions. UC, partnering with UW and others, explored the use of unique communication assets, currently being used by the military in active theaters of operation. This TATRC-funded research involved the use of an unmanned airborne vehicle (UAV).

University of Washington (UW) RAVEN Robot

A U.S. Army-funded research and development project at the UW BioRobotics Laboratory (BRL) recently produced a new telesurgical robot – RAVEN (http://brl.ee.washington.edu). The UC and UW team, lead by Dr. Broderick, was the first to use this system during a collaborative research project entitled HAPsMRT. It was successfully deployed in the high desert of southern California and remotely operated using an UAV-based communication system. This series of tests evaluated a mobile robotic system, deployed in an extreme environment and controlled wirelessly using a small UAV relay station. This capability presents tremendous opportunity to support telesurgical care using mobile systems, where communication assets are challenging.

BODY

RESEARCH PLAN

This telesurgery research was conducted in the extreme environment of the National Undersea Research Center (NURC) Aquarius habitat. The habitat is owned by the National Oceanographic and Atmospheric Administration (NOAA). It is located off the coast of Key Largo, FL, and submerged to a depth of approximately 62 feet. Is serves as a research facility for a variety of organizations, including the Department of Defense (DoD). The U.S. Navy has used it extensively. One program that utilizes this extreme environment is known as NASA Extreme Environment Mission Operations (NEEMO). To date, there have been 13 NEEMO missions, focused on a wide range of research. These missions are technology accelerators. Technology is pushed forward faster when challenged with constraints of remoteness, limited resources, and limited technical expertise.

This telesurgery research, funded by TATRC and reported here, was conducted during the NEEMO 12 mission. NEEMO 12 was a collaborative research and training mission involving an number of organizations, including TATRC, U.S. Navy, U.S. Air Force, NOAA, the University of North Carolina at Wilmington (UNCW), SRI International, UW BRL, HaiVision, and the University of Cincinnati (UC) Advanced Center for Telemedicine and Surgical Innovation (ACTSI). The grant that UC received from TATRC was to support the use of the habitat and to support the telesurgery research tasks.

The telesurgery research, planned and conducted aboard the NEEMO 12 mission, was developed and coordinated by UC, SRI and UW. The Institutional Review Board (IRB) at UC and the Human Protection Research Office (HPRO) Office of Research Protections

(ORP) at the U.S. Army Medical Research and Materiel Command (USAMRMC) reviewed and approved this research. Mr. Charles R. Doarn served as the PI for the research and Dr. Timothy Broderick served as an aquanaut.

Existing partnerships with SRI International, UW BRL and HaiVision were leveraged as well through other UC-funded initiatives.

Science Objectives

1) The development and modification of a robotic surgical system (SRI M7) to incorporate semi-autonomous function of a key medical task (ultrasound-guided needle insertion).
2) Evaluation of a semi-autonomous function of a key task (ultrasound-guided needle insertion) using the modified SRI M7 platform
3) Evaluation of upgraded software capability of the RAVEN to support standardized surgical training tasks.
4) Evaluate the efficiency of different Coder / Decoders (CODECs) in telesurgery applications.
5) Further develop and evaluate the application of wireless telecommunication and available deployable surgical robots in an extreme environment.
6) To build upon prior collaboration and success to catalyze further development of key TATRC relationships and technologies.

Methods – Mission Objectives

A crew of 6 individuals (Table 1) consisting of two non-physician astronauts, a flight surgeon, two habitat technicians, and a TATRC surgeon aquanaut performed research within the Aquarius habitat. The crew remained submerged and lived in the saturated environment for a period of 11 days (May 7-18, 2007). U.S. Navy divers supported the mission on a daily basis.

Table 1. NEEMO 12 Crew

Name	Organization
Heidemarie M. Stefanyshyn-Piper CAPT, USN	NASA
José M. Hernández	NASA
Timothy J. Broderick, MD	UC / TATRC IPA
Josef F. Schmid, MC, USAF	NASA
James Talacek	NURC
Dominic Landucci	NURC

During their 11 day stay in the submerged habitat, the crew conducted a variety of research tasks in telesurgery. UC partnered with SRI and UW to develop, design and direct the advanced medical technology research – telesurgery experiments. This included conducting research and evaluation on two different surgical robots through a telecommunications link, evaluation of a semi autonomous task, and evaluating surgical tasks using the standardized surgical training system – Society of American Gastrointestinal

Endoscopic Surgeons (SAGES) – Fundamentals of Laparoscopic Surgery (FLS) training protocol.

The TATRC grant that UC received only funded the telesurgery activities and use of the habitat.

Telesurgery Research

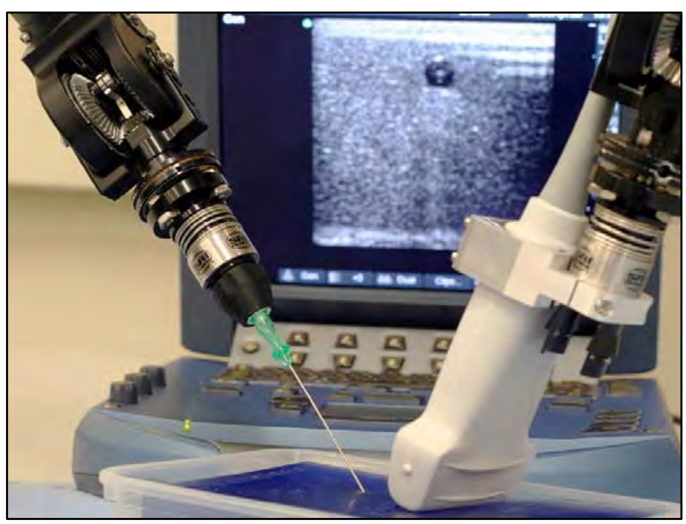
The TATRC-funded telesurgery research involved two different unique robotic systems, the SRI M7 and the UW RAVEN. Both systems required modifications, including hardware and software modifications to enable deployment and operation in the extreme environment of the habitat, and for the M7, the ability to support semi-autonomous functions. Both systems were evaluated in the habitat on separate days during the mission. RAVEN was evaluated on mission day (MD) 2 and MD 3 and the M7 was evaluated on MD 7 and MD 8. Both were also connected to the TATRC booth during the ATA meeting in Nashville, TN. The main thrust was to evaluate semi-autonomous function using a key task – ultrasound-guided needle insertion in a simulated blood vessel.

Prior to the actual deployment of these two robotic systems to the NURC in early May and subsequent integration in the habitat, the UW BRL and SRI modified and streamlined their systems and operations. HaiVision provide use of the Hai1000 Motion Picture Experts Group (MPEG) 4 CODEC.

M7

Preparation

The M7, which had been evaluated in the habitat during NEEMO 9, was updated to accomplish a new set of tasks. The main task was to demonstrate the ability of the system (M7) to mitigate the effects of network latency through the conduct of a semi-autonomous subtask, which was the ability to integrate interoperative imaging with needle-based robotic surgical procedures – ultrasound-guided needle insertion when surgeon and phantom blood vessel are separated by a great distance. This was the main objective of this research task.

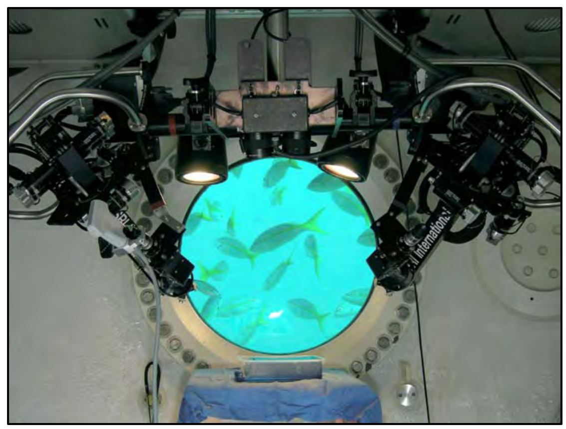


The specific tasks that SRI performed in preparation included: (1) Software and hardware improvements: SRI modified the software to enable scaling of the linear motion between master and slave and to enable the surgeon to clutch (temporarily disengage master/slave control) to allow repositioning to a more comfortable user pose. (2) Restructured control and communication software. SRI redesigned the packet structure used for robotic control to reduce the network bandwidth usage and made other code improvements to perform more reliably in unpredictable network situations. The system was designed to hold its last position in the event of communications interruption. (3) User interface improvements: The master console graphical interface was modified to permit display of ultrasound images in the surgeon console and to support the designation of the target by the operator on the ultrasound image. Graphic overlays were created to assist the surgeon in moving through the steps of the autonomous needle insertion. (4) Support for semi-autonomous needle insertion: Software was created to perform mapping between the 2D target position on the ultrasound image and the location of that target point in 3D space.

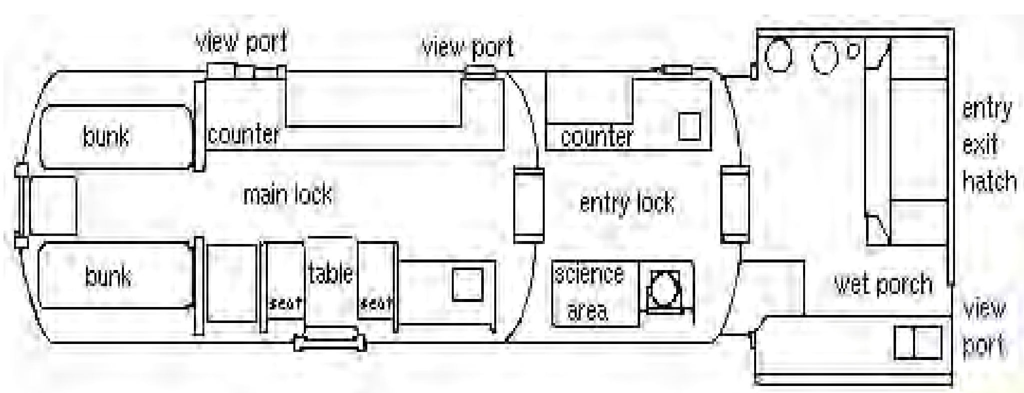
The M7 slave was outfitted with a SonoSite Ultrasound (Sonosite, Bothell, WA) probe. This probe was attached to one of the M7 arms. The other arm was equipped with needle. The objective was to insert the needle from a remote site using the ultrasound probe to guide placement into a phantom blood vessel. (See inset photo)

Deployment and Integration

The M7, which consists of the robotic arm (slave) and control unit (master) was packaged and shipped - the slave to the NURC in Key Largo, FL and the master to the Gaylord Convention Center in Nashville, TN.



Once the slave and ancillary equipment (ultrasound probe, cabling, etc) was received at the NURC, it was processed (repackaged) for potting to the habitat. Once inside the habitat, the system was installed in the bunk room (see inset photo). The crew bunks (6 total) were folded (up or down) to accommodate the placement of the robot. As illustrated in the inset image, the robot arms were suspended from the top two bunks. A table was placed directly underneath to accommodate the phantom blood vessel. The schematic illustrates the layout of the habitat.



The master control unit was deployed in the TATRC exhibit booth at the ATA 12th Annual Scientific Meeting and Exhibition at the Gaylord Convention Center in Nashville, TN. SRI's Mr. Thomas Low and Mr. Kevin Hufford worked to connect the master and slave through a ~1,500 mile connection to the habitat. The local network topology (Nashville) was implemented by a temporary commercial 6 megabits per second (Mbps) IP circuit that supplied dedicated bandwidth to the TATRC booth. During the conducted of the research tasks, all bandwidth was directed to the robotic master to ensure the most robust connection.

Evaluation in the Habitat

The system was evaluated within the habitat and between the habitat and the controllers installed at the ATA exhibit in Nashville, TN. The NEEMO 12 crewmember (Broderick) conducted a series of tests on the robotic system and the communications network.

ATA Event

One of the primary objectives was to conduct a live evaluation of the semi-autonomous, teleoperated needle insertion into a phantom blood vessel with remote image-guidance using an ultrasound probe. Prior to the activity, the NEEMO 12 crew interacted with US Army Medical Research and Materiel Command (USAMRMC) commander – COL Jonathan Jaffin and TATRC leadership – COL Karl Friedl and COL Ronald Poropatich. Two surgeons were supporting the UC/SRI team (Doarn, Harnett, Low, Hufford, and Boulet) in the exhibit/demonstration area – Dr. Mehran Anvari and Dr. Jon Bowersox. Dr. Anvari, Dr. Bowersox, and Mr. Doarn discussed the overall objective of the activity with the assembled leadership on the importance of telesurgery. The team in Nashville then successfully conducted the semi-autonomous task. This marked the first time ever a needle was inserted into a phantom blood vessel using an ultrasound image guidance by someone remotely located from the needle, ultrasound and tissue.

<u>*Semi-autonomous Function*</u>

The key research objective of the M7 was to have a remote surgeon (using master console) control the slave robotic arms, which had been modified and outfitted with a SonoSite ultrasound probe on one arm and a needle on the other.

SRI modified the M7 such that the pedals were used to advance and retract the needle, once the surgeon found the insertion point with the ultrasound probe.

SRI's work was accomplished through a subaward contract with UC. A more comprehensive report on SRI's initiatives appears in Appendix C. This appended report is authored by Mr. Low and Mr. Hufford. This report is a contractual deliverable from SRI to UC.

Lessons Learned

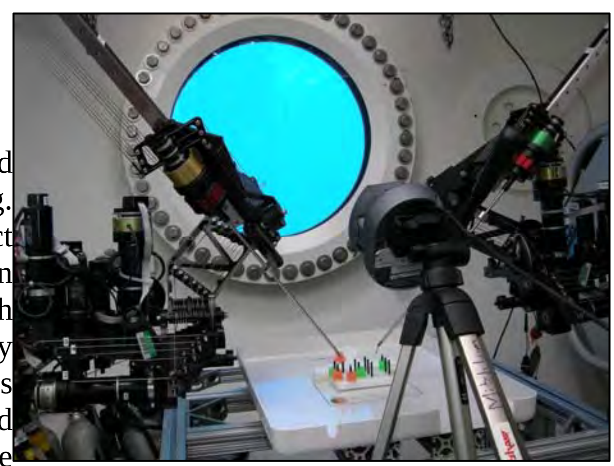
1) The robotic system was not as easy to fix in the austere environment as was hoped.
2) The work flow worked well with software and hardware upgrades.
3) The M7 was able to operate using (1) a smaller master console, (2) overcoming joint-joint control and therefore enabling clutching by the operator, (3) scaling to conduct higher fidelity small scale motion; and (4) semi-autonomous function.
4) Working toward a common task – needle insertion – industry, academia and government overcame a number of deficiencies in design and were able to conduct a specific medical task – needle insertion in a blood vessel using ultrasound-guided imaging.
5) The network was robust and worked without significant issues.
6) The HaiVision CODEC worked fine but had some poor image and audio quality issues.

Recommendations

1) Continue to refine telesurgical and autonomous technologies to accomplish additional military relevant medical tasks.
2) Refine tasks associated with initialization and calibration of the encoders.
3) Modify software to minimize dramatic changes in cable tension.
4) Work all communications issues out upfront, including camera placement and CODEC use.

RAVEN

Preparation



The UW RAVEN robot was originally developed and operated in a laboratory setting using U. S. Army funding. The TATRC-funded and UC-led HAPsMRT project provided an opportunity for the system to be deployed in an extreme environment. This deployment was in the high desert north of Los Angeles and it provided an opportunity to demonstrate the robustness of the system. The lessons learned from that research helped in the modification and preparation of RAVEN for deployment and operation in the habitat. Through a contract with the UC, UW modified the hardware and software of the RAVEN to permit deployment and operation in the habitat.

Deployment and Integration

The RAVEN was shipped to Florida and prepared for potting. Foam casings that would cover the robot arms and fit snugly into a potting dry bag were used. During potting of the RAVEN to the habitat on the weekend prior to the mission, the foam collapsed about the robot arm and pulled off one of the cables. This was fixed in the habitat prior to the start of the mission. Once the system was potted down to the habitat, it was assembled in the bunk room, as highlighted above with the M7. The arms were affixed to a table rather than hanging from the bunks as was the case with the M7.

A team of engineers from UW were also deployed to Florida to support the mission. This team consisted of Ms. Diane Friedman and Mr. Mitch Lum. They provided technical support during the entire mission.

UC sent its RAVEN controllers - Sensable Phantom Omnis - to Nashville to support operations and evaluation between the ATA convention site and the NURC. UC also installed controllers at the CMC to support the outreach event.

Evaluation in the Habitat

Once the RAVEN was assembled in the habitat, tests were conducted to determine communications connectivity with the NURC and with ATA convention site. The robot was manipulated from three different sites – (1) UW BRL; (2) NURC; and CMC. Data was collected on the motion of the system, including position velocity and torque of the manipulator arms (end effectors). Data was recorded while surgeons performed standard SAGES FLS tasks. Data analysis is underway.

The system was also used to simulate rock manipulation, and it was used to support the CMC event, where school children operated the robot.

CMC Event

Prior to the mission, teams of middle school students from multiple schools from Ohio and Indiana competed in a robotic surgery “competition” at UC’s Center for Surgical Innovation (CSI). These children had a great time with “hands on” learning that was focused on science, medicine, engineering, and robotics.

During the mission, these students met the crew via videoconference between the CMC and the Aquarius habitat. Students also remotely operated the RAVEN surgical robot in the habitat.

Connection to the CMC used the same configuration as the M7 did to Nashville. Since the CMC had only a T-1 (1.54 Mbps) IP network link, the local carrier, Cincinnati Bell, reconfigured the connection to a “burstable” LAN Advantage connection with a maximum bandwidth of 5 Mbps. This permitted a more robust network.

ATA Event

The RAVEN controllers - Phantom Omnis - were deployed to the Gaylord Convention Center to support demonstration of the ability to manipulate the RAVEN. Small foam blocks were set up on a table at the NURC. The users at the controls in Nashville were able to manipulate the RAVEN arms, located at the NURC. The foam samples were picked up and moved around.

UW’s work was accomplished through a subaward contract with UC. A more comprehensive report on UW’s initiatives appears in Appendix D. This appended report is authored by Dr. Blake Hannaford and his team at UW. This report covers the contracted work that UW performed.

Lessons Learned

1) The RAVEN was difficult and bulky to deploy. This required a UW engineer to dive into the habitat to make repairs.
2) It took some time to set up
3) The network was robust and worked without significant issues.
4) The HaiVision CODEC worked fine but had some poor image and audio quality issues.

Recommendations

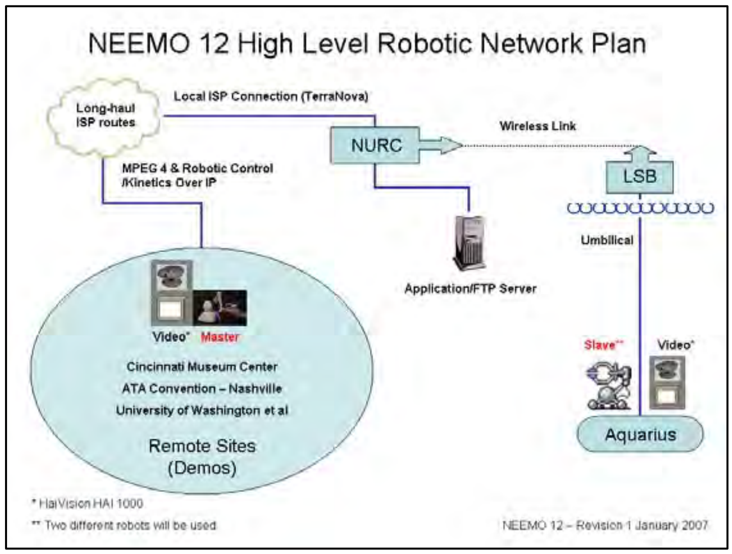
1) Continue to refine robotic and telesurgery technology to accomplish additional military relevant medical tasks.
2) Continue to refine steps to decrease deployment time.
3) Work all communications issues out upfront, including camera placement and CODEC use.

Telesurgery Telecommunications Network

The NEEMO 12 mission used the same local NURC network used in prior NEEMO missions. The network was improved with upgraded Cisco equipment. Once communications reached the local Internet Service Provider (ISP) external to the NURC, it was completely different than prior NEEMO missions.

The Aquarius is a subnet on a Local Area Network (LAN) of the NURC. The connection from the mainland to the Aquarius is facilitated by a Spectra 5.4 GHz Wireless Bridge/ minimum 30 Mbps link from an antenna on the roof of the facility to the Life Support Buoy (LSB) (floating in the ocean just above the habitat) where a Cisco switch is located. An umbilical connects the network and other life support cables to the Aquarius. The NURC is connected to the Internet by TerraNova, a commercial ISP where standard Internet Protocol (IP) routing takes place. The network communications for the command and control of both robots was facilitated using Transmission Control Protocol/IP (TCP/IP) by way of this topology. The audio and video for the robotic sessions was also transported using this topology and related protocols such as UDP (User Datagram Protocol) and MPEG4. Because there were two robotic platforms for NEEMO 12, it was imperative to achieve a high degree of technical interoperability to minimize risks and reconfiguration. The inset diagram illustrates the basic communications topology.

There were numerous firewall, addressing and port configuration issues to deal with at each endpoint. For example, certain ports had to be opened on the respective firewalls to allow specific packets to pass, in and out. This spanned the videoconferencing and kinematics control data.



Both robots utilized the same video CODEC (HaiVision Hai 1060), network protocols and bandwidth. The HaiVision is an MPEG4 AVC H.264 CODEC. The aquanauts were trained on operation of the HaiVision CODEC but once connected to the Aquarius network it was remotely configured and tuned by Mr. Lance Boulet of HaiVision at each site.

The CODEC encoded video stream so that it could be viewed on a laptop as the remote sites. Although picture quality was excellent, there was a noticeable latency of approximately 500 – 1,000 millisecond. This was due to compression and decompression as the latency of the Internet was measured at about 70 ms.

The RAVEN also utilized iChat (V.2.1.3) for the Apple Macintosh.

Technology Summary

The challenges of implementing the technology were numerous. Beyond the fact that each robot is experimental, each site presented unique challenges. As mentioned earlier, at the NURC and Aquarius habitat, the challenges were mitigated by the highly interoperable design efforts. For example, the mounting superstructure was designed to support both robotic platforms even though the M7 hung from an overhead perspective and the RAVEN used a floor/table mount.

Network configurations were much more challenging. The microwave connection was very reliable and efficient as was the connection to the Internet through TerraNova. However, the connections in Cincinnati and Nashville were difficult. At the CMC, outdated infrastructure, old devices and minimal bandwidth necessitated creative solutions.

In Nashville, TATRC and UC coordinated access to a 6 Mbps line. This was delayed due to scheduling constraints, and therefore, impacted pre-testing.

Once the various issues were resolved at all locations, the interactions took place successfully.

PROJECT TIMELINE

Preparation for the mission occurred in the months prior to splash down. The crew announcement and seminar were held at UC in March 2007. Splash down (the actual diving to Aquarius) took place on May 7, 2007. This mission lasted until May 18, 2007, when the crew splashed up (surfaced).

MANAGEMENT AND ORGANIZATION

The UC team consisted of the PI, Mr. Doarn, Mr. Brett Harnett, Ms. Elyssa Westrich and Dr. Broderick. During the months preceding the mission, the UC team participated in MMT meetings, which were held weekly. These meetings, held by teleconference, were also attended by a variety of other personnel, the NEEMO crew and TATRC's Ms. Nita Grimsley.

The organizations and their representatives involved in the telesurgery experiments included UW – Mitch Lum and Diana Freeman; HaiVision – Lance Boulet; SRI – Thomas Low and Kevin Hufford; CMAS – Dr. Mehran Anvari; and COL Jon Bowersox, MC, USAF-Ret – UC and Cincinnati VA Hospital. Each participant also included a number of other individuals as well.

In order to organize the use of the Aquarius Habitat a Memorandum of Understanding (MOU) was established between UC, NASA JSC and UNCW. This was supplemented with a subaward contract between UC and UNCW for the operational use of the habitat.

The conduct of this research also involved a requirement for having research reviewed by the Institutional Review Board (IRB) at UC and the U.S. Army's HPRO ORP.

KEY RESEARCH ACCOMPLISHMENTS

The conduct of the NEEMO 12 mission had a number of key research accomplishments. These are listed below in two categories – Primary and Secondary. These include the following:

Primary

1. Developed and conducted research on the world's first semi-autonomous ultrasound-guided needle insertion, where surgeon and simulated blood vessel were separated by some distance. The surgeon, located at the TATRC exhibit area during the ATA meeting in Nashville, used the M7 master controller to position the ultrasound probe remotely and then the robot autonomously inserted a needle into the phantom blood vessel.
2. Successfully deployed two unique surgical robotic systems in an extreme environment and operated them remotely over a wireless communication system.
3. The NEEMO 12 crew conducted a variety of research activities focused on conducting telesurgery in remote and extreme environments.
4. Brought together a world-class team of telesurgery experts to conduct research, including expertise at UC, UW, SRI and involving Dr. Bowersox and Dr. Anvari.
5. Ensured that the robotic systems were easily assembled and disassembled such that users (as opposed to the developers and engineers) could deploy them in an extreme environment.
6. Began to integrate and these systems and thereby work toward the goal of a standard distributed autonomous therapeutic robotic platform/system.

Secondary

1. Held a crew announcement at the University of Cincinnati in March 2007. This also provided an opportunity for a special panel discussion on remote healthcare. In addition to the crew, the panel discuss include business leaders, engineers, and medical personnel. TATRC personnel, Dr. Christian Macedonia and Ms. Nita Grimsley participated.
2. Conducted a robotics competition at the University of Cincinnati. The winners of the competitions were permitted an opportunity to drive the RAVEN robot, while it was deployed in the habitat. This was conducted from the CMC.
3. UC team conducted a live telesurgery demonstration to TATRC leadership (COL Jonathan Jaffin and COL Ronald Poropatich) along with ATA leadership in the TATRC booth at the ATA meeting in Nashville, TN.
4. Utilized the RAVEN of rock manipulation. Scientist was remotely located from the robotic system and rocks. This demonstrated dual use, which can be a valuable tool when resources are constrained.

REPORTABLE OUTCOMES

The NEEMO 12 program continues to receive a lot of attention from the press, and there were significant outcomes from this work. The work accomplished in support of NEEMO 12 has been reported in many ways. The aforementioned accomplishments, most notably the semi-autonomous needle insertion, have been and will be reported in a variety of venues. These are enumerated below. In addition to this final report, this TATRC-funded research will be published and presented. There has been significant media coverage of this research. All of the outcomes are reported below. Data analysis continues and TATRC will be acknowledged in all peer-reviewed publications and presentations.

Intellectual Property

There is no intellectual property to report from this research.

Abstracts

1. Doarn CR. Surgical Innovation. Medical Automation International 2007 – Vital Signs: Saving Lives, Cutting Costs. National Conference Center, Lansdowne, VA, October 2007.
2. Doarn CR. Telesurgery: What has been done to date? Second Intensive Telemedicine and e-Health Seminar that International Virtual e-Hospital Foundation, Tirana Albania, October 2007. *Telemed and E Health. At Press.*
3. Doarn CR. Hannaford B, Low T, Broderick TJ Robotic Telesurgery Applications in NEEMO 12. 13th American Telemedicine Association, Seattle, WA. April 2008. *Accepted.*
4. Moses GR, Doarn CR. Barriers to Wider Adoption of Mobile Telerobotic Surgery: Engineering, Clinical and Business Challenges. Medicine Meets Virtual Reality 15. Long Beach, CA. February 2008. *Accepted.*
5. Lum MJH, Friedman DCW, King H, Sankaranarayanan G, Rosen J, Broderick TJ, Sinanan MN, Hannaford B. Raven – A Surgical Robot for Teleoperation. 13th American Telemedicine Association, Seattle, WA. April 2008. *Accepted.*

Presentations

1. Doarn CR. Building a Tele-Trauma Program. Providing Surgical Interventions from Remote Locations. World Healthcare Innovation and Technology Congress 3.0 – Innovation to Transform. Washington, DC. December 2007
2. Doarn CR. Surgical Innovation. Medical Automation International 2007 – Vital Signs: Saving Lives, Cutting Costs. National Conference Center, Lansdowne, VA, October 2007.
3. Doarn CR. Telesurgery: What has been done to date? Second Intensive Telemedicine and e-Health Seminar that International Virtual e-Hospital Foundation, Tirana Albania, October 2007
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5. Broderick, TJ. Recent Advances in Robotic Telesurgery. 16th Society of Laparoendoscopic Surgeons Annual Meeting and Endo Expo 2007, San Francisco, CA: September 2007.
6. Lum M, Friedman, D, King H, Donlin R, Sankaranarayanan G, Broderick TJ, Sinanan M, Rosen J, Hannaford B. Teleoperation of a Surgical Robot via Airborne Wireless Radio and Transatlantic. The 6th International Conference on Field and Service Robotics, Chamonix, France: July 2007.

Publications

1. Doarn CR, Hufford K, Low T. Rosen J, Hannaford B. Telesurgery and Robotics: A Roundtable Discussion. *Telemed and E Health* 2007; 13(4):369-380.
2. M. Lum, et. al. Objective Assessment of TeleSurgical Robot Systems: Telerobotic FLS. Proceedings of MMVR 2008, Long Beach, CA, January 2008. *At Press*
3. Sankaranarayanan G, Potter L, Hannaford b. Measurement and Simulation of Time Varying Packet Delay with Applications to Networked Haptic Virtual Environments,' Proceedings of Robocom 2007, Athens, Greece, October 2007.
4. Sankaranarayanan G, King H, Ko SY, Lum MJH, Friedman D, Rosen J, Hannaford B. Portable Surgery Master Station for Mobile Robotic Telesurgery. Proceedings of Robocom 2007, Athens, Greece, October 2007.

News Coverage (Television, Radio, Print Media. And Web)

UC

March 2, 2007
WKRC-TV, Channel 12
Recorded pre-mission story about NEEMO 12 featuring Dr. Timothy Broderick. Talking about overall objectives of the mission. Reported by Paul Adler during the 6 a.m. and 7 a.m. morning broadcasts.

March 6, 2007
The News Record (UC student-run newspaper)
Brief pre-mission news story featuring Dr. Broderick, detailing NEEMO 12 science objectives.

March 6, 2007
WXIX-TV/Fox 19
Live morning show appearance by Dr. Broderick and Heidi Stefanyshyn-Piper on local Fox 19 morning show to talk about upcoming mission and local outreach events.

May 7, 2007
WNKU-FM/89.7 FM—Northern Kentucky NPR
Pre-recorded interview featuring Mr. Charles Doarn, talking about the upcoming NEEMO 12 mission and the junior high robotics competition, hosted by UC.

May 9, 2007
WKRC-TV/CBS, Channel 12
Pre-recorded segment showing undersea NEEMO 12 team talking to children at a community outreach event at the Cincinnati Museum Center, hosted by UC. Reported by Liz Bonis at 5 p.m.

June 1, 2007
WKRC-TV/CBS, Channel 12
Pre-recorded morning show interview with Dr. Broderick, on NEEMO 12. Reported by Paul Adler during the 6 a.m. and 7 a.m. broadcasts. The story talked about results of the mission and featured video and still photos from when the team was undersea.

June 10, 2007
WVXU-FM/91.7 FM—Greater Cincinnati NPR
Pre-recorded segment featuring Dr. Broderick and his recent involvement in the NEEMO 12 mission. Aired during "Cincinnati Edition" around 7:50 a.m.

UC PUBLICATIONS

Findings, April 2007
Pre-mission feature story detailing UC involvement in NASA NEEMO 12 mission and science objectives. Newsletter has a wide distribution to faculty, staff and friend of UC as well as university clinical practice areas.

Findings, May 2007
Pre-mission photo story about local robotics competition tied to NEEMO 12 mission and science objectives.

Findings, June 2007
Photo story showing local student remotely "driving" the surgical robot from the Cincinnati Museum Center during the NEEMO 12 undersea mission.

OTHER
Dr. Broderick was also interviewed on Tuesday, July 3 at 1:30 p.m. about telemedicine and robotics for a show that will air on National Geographic and the Armed Forces Network.

SRI, International

SRI has a number of citations of news reports. These are highlighted in their report. See Appendix C.

UW - BRL

UW has a number of citations of news reports. These are highlighted in their report. See Appendix D.

MILITARY RELEVANCE

Provision of emergency diagnostic and medical care in an extreme environment is of significant interest to the U.S. Army. This research represents an important step in the evolution of surgical robotics from telesurgery to distributed autonomous therapeutics that includes remote supervisory-controlled, semi-autonomous robotic function. This research marked the first time ever that a surgeon, remotely located from the robotic system and simulated tissue, was able to insert a needle into a blood vessel using ultrasound-image guidance. More importantly, the robotic system was able to autonomously insert a needle into a simulated blood vessel. Further distributed autonomous therapeutics research is indicated Robotic telesurgery and autonomy have been identified by TATRC as a prime area of medical research for the next decade. These technologies represent key components of DARPA's and the U.S. Army's Trauma Pod Program. NEEMO 12 research has been a natural progression from the work conducted in NEEMO 7 and NEEMO 9.

NEEMO 12 has also provided a foundation for leverage of diverse experience and resources of multiple branches of the U.S. military, which has been characterized in prior NEEMO missions. Collaboration across traditional government barriers has accelerated medical technology development as demonstrated by multiple NEEMO scientific and popular presentations/publications. NEEMO 12 built upon prior collaboration and success to catalyze further development of key TATRC relationships and technologies.

BUDGET

The value of this award was $244,543. An apportionment of $75K was sent directly to NASA JSC through an interagency transfer. The UC grant was $169,543. A subaward in the amount of $110,000 was established with UNCW for use of the Aquarius Habitat. The remainder of the funds was used to support salary, fringe, travel and equipment at UC. Dr. Broderick's participation was part of his assigned task as an IPA with TATRC. The funds were spent in accordance with the budget as it was submitted.

The subaward contracts with SRI and UW were accomplished through the TATRC-funded Advanced Center for Telemedicine and Surgical Innovation (ACTSI) grant.

CONCLUSIONS

TATRC-led robotic surgery development has continued with this research. During this mission, two surgical robotic systems, the SRI M7 and the UW RAVEN were modified and deployed in an extreme environment, the Aquarius Habitat. This habitat is an ideal research platform to spur collaborative accelerated development of advanced medical technology for use in extreme environments. Both systems were successfully deployed, assembled and dissembled by trained personnel, and the systems were shown to be effectively controlled from remote sites.

The robotic telesurgery research brought together academia, industry, and government to expand understanding of robotic telesurgery in extreme environments. The research partners included NOAA/UNCW (telecommunication), TATRC, UW, SRI, and HaiVision.

This funded research had several key activities (1) evaluate the ability to perform a semi autonomous task, (2) deployment of two different surgical robots in the extreme environment and evaluate their performance; and (3) build upon relationships to move telesurgery forward.

During this research, both robotic systems were operated remotely. This was accomplished using a robust and reliable telecommunications link between the habitat and several other locations. A link was established between the habitat and the convention center in Nashville to support the TATRC exhibit at that ATA annual meeting. During this link, TATRC leadership discussed telesurgery with Drs. Anvari and Bowersox and Mr. Doarn. The assembled group interacted with the NEEMO crew. A surgeon in Nashville conducted the first semi-autonomous, ultrasound image-guided needle placement in a simulated blood vessel using the M7.

A second set of telesurgery tasks that were conducted using the UW RAVEN. These tasks included remote surgeons conducting basics surgical tasks on the SAGES FLS training system. The RAVEN was also controlled by several individuals remotely located. These individuals manipulated various simulated structures in the habitat over the telecommunications link. The users were located in Cincinnati, Key Largo, Nashville, and Seattle.

Both systems demonstrated the ability to be deployed in an extreme environment by novice users and operated from a distant site. A key milestone was the remote semi-autonomous insertion of a needle in a simulated blood vessel using a scalable telecommunications link and a modified telerobotic surgery system (M7). This research suggests that evolution from telesurgery to distributed autonomous therapeutics can overcome operational communication issues routinely encountered during military conflict.

Provision of emergency diagnostic and medical care in an extreme environment is of significant interest to the U.S. Army. This project substantially furthered military robotic surgical research and represents an important step in our march toward a deployable robotic system that improves the access to and quality of care on the battlefield.

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APPENDICES

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Appendix A

Contact Information

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Appendix B

Acronyms

ACTSI	Advanced Center for Telemedicine and Surgical Innovation
ATA	American Telemedicine Association
BMIST	Battlefield Medical Information System-Tactical
BRL	BioRobotics Laboratory
CODEC	Coder / Decoder
CMAS	Center for Minimal Access Surgery
CMC	Cincinnati Childrens Museum
CMO	Chief Medical Officer
CSI	Center for Surgical Innovation
DARPA	Defense Advanced Research Projects Agency
ELAN	Extended Local Area Network
FLS	Fundamentals of Laparoscopic Surgery
HAPsMRT	High Altitude Platforms for Mobile Robotic Telesurgery
HPRO	Human Protection Research Office
IP	Internet Protocol
IRB	Institutional Review Board
ISP	Internet Service Provider
Kbps	Kilo bits per second
LAN	Local Area Network
LSB	Life Support Buoy
Mbps	Mega bits per second
MMT	Mission Management Team
MOU	Memorandum of Understanding
ms	millisecond
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environments Mission Operations
NOAA	National Oceanographic and Atmospheric Administration
NSBRI	National Space Biomedical Research Center
NURC	National Undersea Research Center

OPR	Office of Research Protection
SAGES	Society of American Gastrointestinal Endoscopic Surgeons
SRI	Stanford Research Institute
TATRC	Telemedicine and Advanced Technology Research Center
TCP/IP	Transfer Control Protocol/Internet Protocol
UAV	Unmanned Airborne Vehicle
UC	University of Cincinnati
UNCW	University of North Carolina at Wilmington
USAMRMC	United States Army Medical Research and Materiel Command
UW	University of Washington

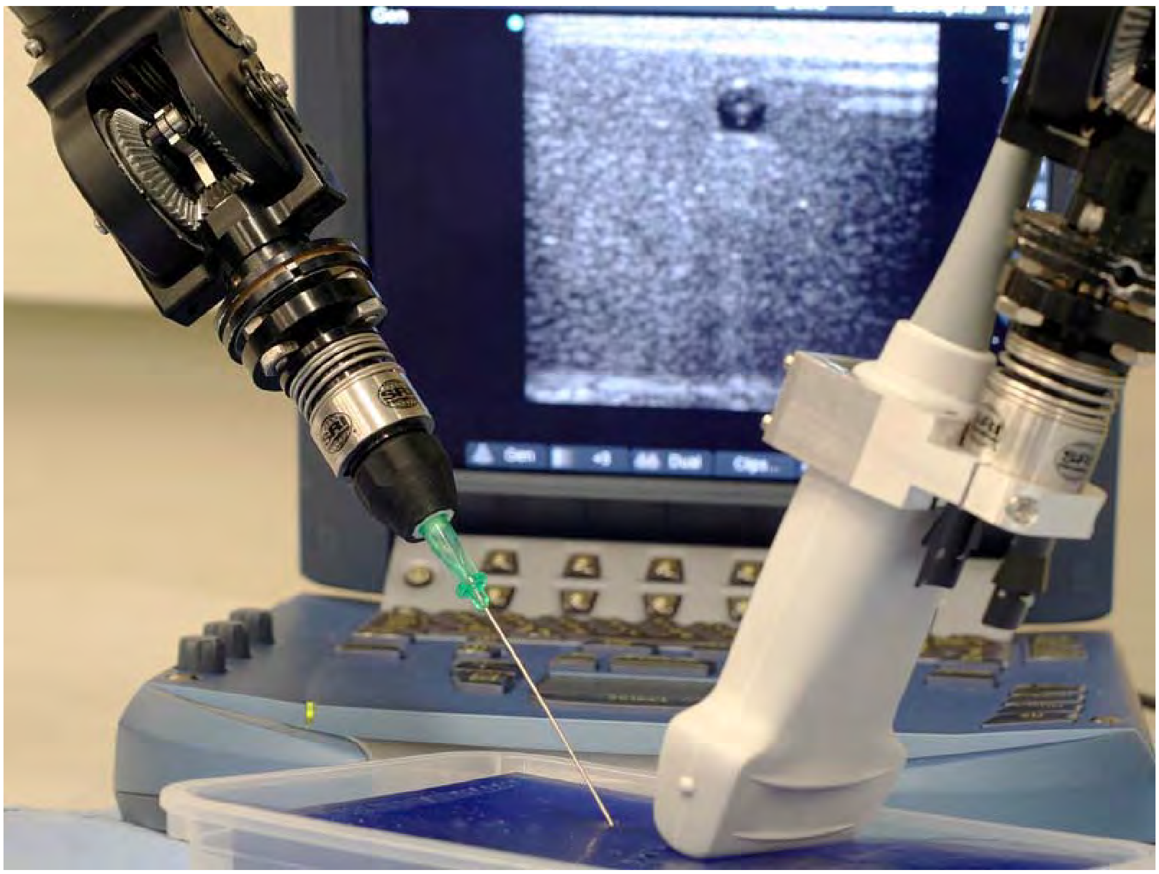
Appendix C

<u>SRI Report</u>

The appended report is as it was prepared by the SRI. It has been formatted to fit this final report.

NEEMO 12 Report
SRI International

Prepared By:
Kevin Hufford
Thomas Low
SRI International
12/04/07



Purpose

The NEEMO 12 teleoperation experiments demonstrated the ability of a robotic system to mitigate the effects of network latency through the conduct of autonomous robotic subtasks. It demonstrated the feasibility of integrating interoperative imaging with needle-based robotic surgical procedures, an important milestone for the use of robotics for trauma care. The capability of a robotic system to perform surgical subprocedures autonomously is an important step toward mitigating the impact of communication latency caused by long distance teleoperation.

The use of telerobotics for delivery of life-saving procedures in the battlefield, in space, or during patient evacuation is of interest to both NASA and the military. Presently, there is a shortage of critical care air transport teams; telerobotic capabilities could serve as a force multiplier to enable teams to transport more patients and allow transport with less skilled teams. The ability to perform simple procedures could allow less skilled providers to care for increasingly ill patients. Automated telerobotic intensive care unit services provided remotely by an intensivist and supported in air by a technician will both improve care and reduce the logistical footprint of the process.

Goals

The NEEMO analogue missions are the execution of space processes within the Aquarius underwater laboratory in Key Largo, Florida. Performing innovative medical procedures in this remote environment allows astronauts and their support crews to evaluate and train for the adoption of such techniques within extreme conditions of space missions.

SRI's participation in NEEMO 12 focused on demonstrating a combined teleoperated and autonomous robotic medical task, using both stereo video and ultrasonic imaging to locate and insert a needle into fluid-filled tube contained within a tissue phantom. The primary objective was to evaluate the use of autonomous robot function as a means to overcome latency. Further, the experiments demonstrated the ability of non-specialists in an extreme environment to rapidly deploy a two-armed teleoperation system with stereo vision and diagnostic and interventional imaging capabilities.

Accomplishments

The goal of this experiment was fully met. The master control console was set up on the show floor of the ATA 2007 conference in Nashville, TN. The slave robot was deployed in the Aquarius habitat off the coast of Key Largo, FL. A live demonstration of the remote image-guided needle insertion was successfully performed for attendees of the ATA conference.

Figure 1: M7 Master console

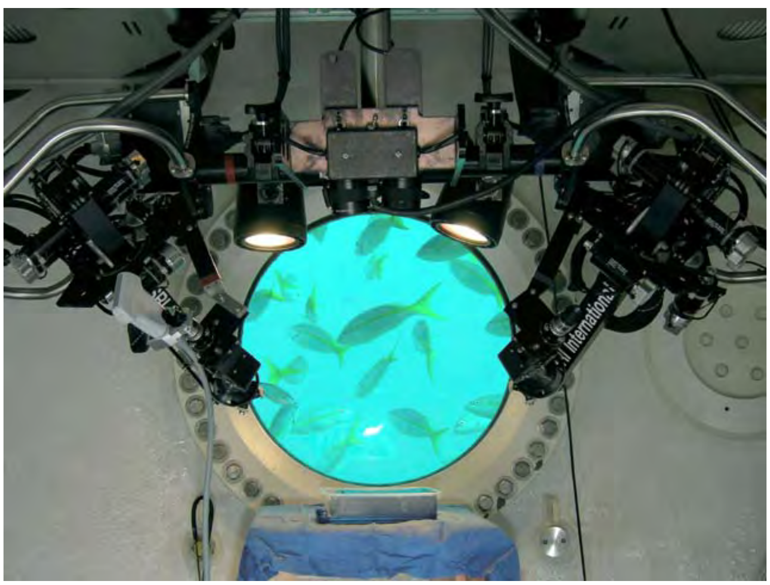


Figure 2: M7 Robot as deployed in Aquarius habitat (Photo credit: NASA)

Figure 3: M7 Robot holding ultrasound probe and needle

Workflow

A remote image-guided needle insertion follows the sequence below.

1. Surgeon places ultrasound probe on vessel phantom (Figure 4).
2. Surgeon orients ultrasound probe while viewing image. Pressure applied to phantom is maintained by robot. Position and attitude of probe is adjusted through teleoperation (Figure 5).
3. Surgeon positions needle to point on desired insertion path using stereo view (Figure 6).
4. Surgeon uses master console to view ultrasound image and to select target on ultrasound image. Tip of needle is held fixed during target selection, but needle orientation is continuously updated to align with target. (Figure 7).
5. When commanded, robot autonomously inserts needle along its axis to target point depth (Figure 8-Figure 10). Surgeon views in 3-D.
6. When commanded, robot retracts needle out of vessel phantom and returns control to surgeon (Figure 11).

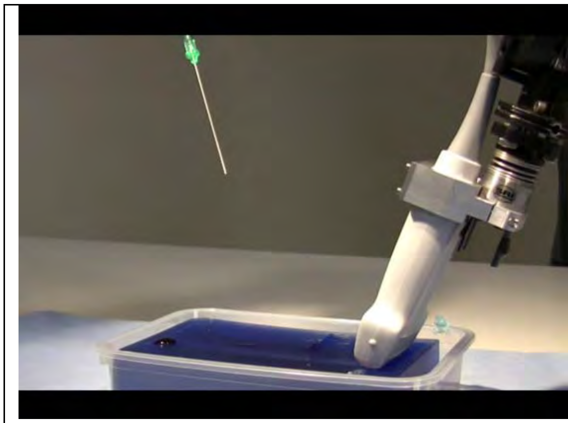


Figure 4: Surgeon positions probe on phantom

Figure 5: Surgeon orients probe for best image

Figure 6: Surgeon positions needle at insertion point

Figure 7: Surgeon moves target cursor on ultrasound image and selects insertion target

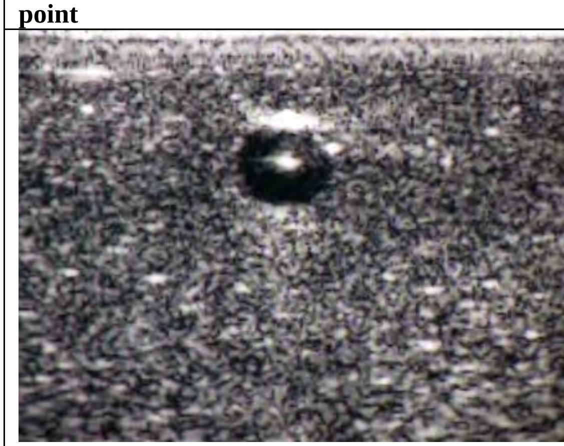


Figure 8: Ultrasound before needle insertion

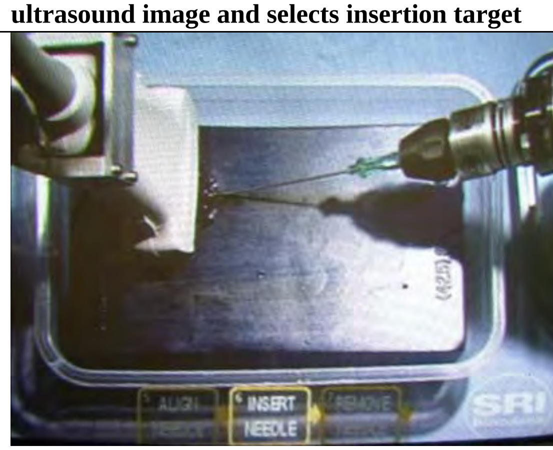


Figure 9: Robot inserts needle to target

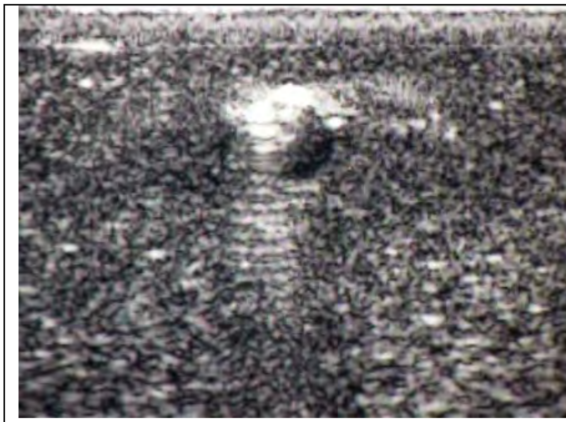


Figure 10: Ultrasound showing needle insertion

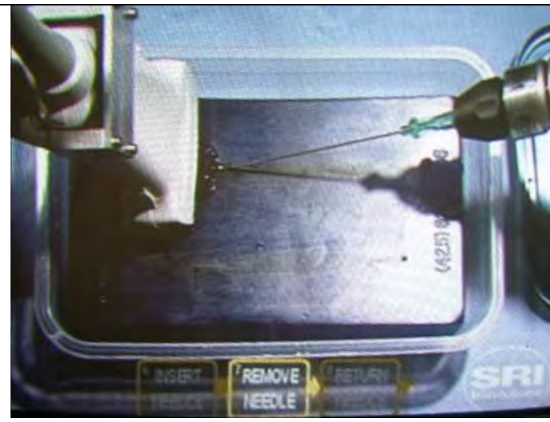


Figure 11: Robot removes needle, returns control to surgeon

Budget

At the initiation of the project, the M7 robotic system was a functional telesurgery system, but the software architecture at the time did not allow for significant development beyond the current capabilities of the system. At the initiation of the project, the system functioned as follows:

- **Similar Master and Slave kinematics required:** The master and slave robotic systems were kinematically similar, requiring a large master console, and restricting control of the slave robot to a single master console.

- **Joint to joint control:** Due to the kinematic similarity of master and slave, the system functioned by transmitting the encoder values of each individual joint of the master control arms to the corresponding joint on the slave robot arms.

- **No clutching:** As a result of the joint-to-joint control, it was not possible to allow the surgeon to clutch, or disengage control momentarily, to allow him to reposition his hands to a more comfortable working pose.

- **No Scaling:** Due to the kinematically-similar master and slave, it was possible for the surgeon to reach nearly all of the workspace of the slave robotic system. However, it was not possible to scale the surgeon’s motions down to allow better performance in delicate operations requiring high-fidelity small-scale motion.

- **No Autonomous Action:** The slave follows the master, but could not be commanded to move in a prescriptive manner.

To enable the robotic demonstration for NEEMO 12, SRI developed:

- **Forward and inverse kinematics iterative solution:** Prior SRI IR&D funded development of closed-form forward and iterative inverse kinematic solution was leveraged to permit conversion between real-world Cartesian coordinates and robot joint encoder values. This capability was vital, for it provided the ability to issue autonomous position commands as demonstrated during NEEMO 12, as well as permitting the use of a smaller, kinematically-dissimilar master controller, as demonstrated in experiments since NEEMO 12.

- **Graphical Simulation** (funded by SRI IR&D): A 3D graphical simulation of the robot kinematics, developed on SRI internal funds, allowed new algorithms to be tested as a safety precaution before committing the M7 robot hardware. This simulation also permitted simultaneous coding by multiple developers without being limited to sharing a single piece of hardware.

- **New communication protocol (incremental moves) packet:** A new command packet structure from the master to the slave was created that incorporated incremental motion commands. These incremental position commands prevent large jerks in position that could otherwise be seen if an intermediate absolute position command was lost.

- **Restructured control and communication software:** SRI redesigned the packet structure used for robotic control to reduce the network bandwidth usage and made other code improvements to perform more reliably in unpredictable network situations. The system was designed to hold its last position in the event of communications interruption.

- **Slave status packets containing achieved position data:** Status packets, otherwise known as “heartbeats”, sent back multiple times per second from the slave robotic system, were implemented and contain the current position data, which was then be used to verify that the commanded position was achieved. If communication is lost between master and slave, the system remains in a safe state. When communication is restored, the operation resumes seamlessly.

- **Clutching:** SRI modified the software to enable scaling of the linear motion between master and slave and to enable the surgeon to clutch (temporarily disengage master/slave control) to allow repositioning to a more comfortable user pose.

Software and Hardware improvements:

- **Calibration Technique for determination of world to arm coordinate transformation.** To permit each arm to be commanded to a pose is space, one must first know precisely the position and orientation of each arm’s base in the world coordinate frame. SRI developed a software program to determine these reference frames experimentally. A straight edge is placed on the work surface, aligned with first the X axis, and then the Y axis. These axes were projected onto the work surface with a laser cross hair projector. A stylus–like tool in inserted in the tool holder, and each arm manually moved along the straight edge. At points along each axis are digitized, and a least squares 3-D line fitted to the cloud of points. These two lines for each arm determine the arms X and Y axis. The Z is obtained by taking the cross product of these two vectors. The base transformation matrix that locates each arm is determined by constraining the X and Y axes of each arm to correspond in space.

- **Trapezoidal velocity motion profile:** To provide for a smooth motion profile for needle insertion, a trapezoidal velocity motion profile was used when planning the automated move. Interpolation was performed in world space. The linear path of the move was divided into non-uniform-length steps to provide a smoother start and stop to the needle insertion.

- **User Interface Improvements:** SRI developed a GUI to permit untrained operators to use the system. This entailed digitization of three video streams from the ultrasound instrument and from the left and right eye cameras. A video capture card (Eurosys Piccolo Tetra) capable of four channels of NTSC video capture was installed in a PCI express buss industrial PC. Depending on the step of the procedure, either the ultrasound video or stereo camera video was presented in the surgeon console. Overlaid on the lower part of the image were step-by-step procedure instructions, indicating the present task, the next task (to the right) and the previous task (to the left). These transparent overlays were generated using an Nvidia 7800 GTX graphics processor in the industrial PC case. Each CRT monitor in the master console was connected directly to the graphics card output using special cables to combine horizontal and vertical sync into a composite sync signal. Foot pedals were used to permit the operator to advance to the next step, or when appropriate, to revert to the previous step. A third foot pedal was used to clutch or disconnect the slave fro the master. When pressed, master control movement was not transmitted to the slave, but packets with zero movement increment were transmitted to prevent the slave from going into a loss of signal safe mode.

- **Hardware adapter to hold needle and probe:** To enable the experiment, it was necessary to design adapters for both the needle and ultrasound probe. These adapters connected the universal tool interface at the end of the robot arms with the needle and ultrasound probe, respectively. In addition, the necessary kinematic changes were made in software to provide correct robot motion depending on the tool that was inserted.

- **Structure modifications to support structure in the habitat:** Partnering with the University of Washington researchers, a support structure was designed to mount the M7 slave robot in the Aquarius habitat. This extruded aluminum structure was required to be easily deployable and to mount on the edges of the bunks in the habitat. The structure was designed so that the vast majority of it would be useful for both the M7 and Raven robots.

- **Servo rates on PMAC raised:** To provide smoother motion and a more tightly-controlled servo system, the servo loop closure rates of the servo motion controller cards for the M7 robot arms (called PMACs) were raised to 2 kHz. These PMAC cards provide high-speed low-level servo loop closure, while the commands transmitted from the master to the slave were sent at a lower rate – approximately 200 Hz during the NEEMO 12 experiments.

- **Support for autonomous needle insertion:** Software was created to perform mapping between the 2D target position on the ultrasound image and the location of that target point in 3D space. More details on the overall software architecture may be found below under the Autonomy Overview

NEEMO 12 Mission Support: SRI staff members prepared the M7 equipment for shipment to and from the Nashville, TN and Key Largo, FL sites and were present onsite in Nashville, TN during performance of the experiments.

Autonomy Overview

During the initial portion of the needle-insertion procedure, the slave robot was manipulated by the surgeon sitting at the master console in normal teleoperated mode. In this mode, as the surgeon moved the arms of the master console, the differential position packets in Cartesian coordinates were transmitted to the slave robot, whose arms then moved to the commanded positions.

During subsequent steps of the procedure, some of the directions of motion were restricted for safety and ease of use of the system by the surgeon. Upon transition into the autonomous portion of the procedure, the surgeon's only inputs were two pedals—one of which advanced the system through the steps of the procedure, and the other which reverted the system to the previous step.

After the autonomous removal of the needle, the next state returns normal teleoperation control to the surgeon. Figure 12 shows a brief state machine diagram illustrating transitions between autonomous and teleoperated control.

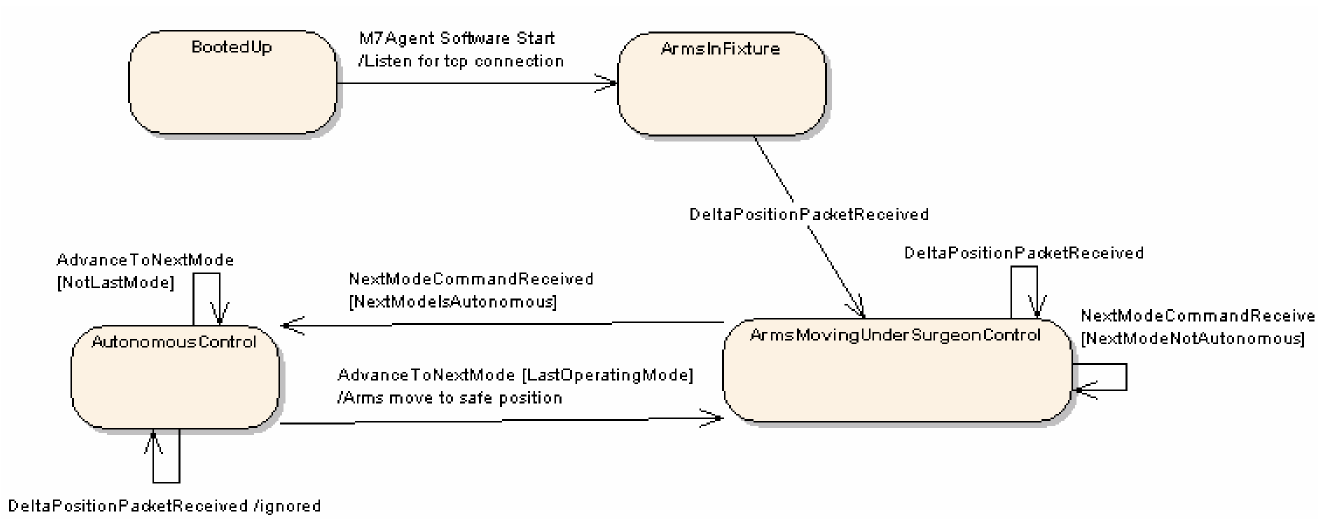


Figure 12: Control moves between surgeon teleoperation and autonomous control depending on the next logical state for a needle insertion procedure.

State Machine

Three foot pedals allowed the surgeon to clutch, move through the procedure, and revert to the previous step in the procedure, respectively. However, since returning to a previous state would have resulted in an unsafe situation during certain portions of the procedure, all state machine transitions were verified to move to safe, logical conditions based upon the current state. For instance, after autonomous needle insertion, simply returning to the "position needle" phase could result in undesired motion of the needle inside the tissue. Thus, as a safeguard, pressing on the "back" pedal after an autonomous needle insertion resulted in an autonomous needle removal along the needle axis to a safe position above the tissue. Once the needle had been fully retracted, teleoperation control was returned to the surgeon for needle re-positioning.

Constraints of motion depending on current state

Depending on the current step in the sequence, the permitted directions of motion of the robot were constrained for reasons of safety and ease of use by the surgeon. For instance, during placement of the ultrasound probe on the vessel phantom, the surgeon interacts with the system using a 3-D stereoscopic view. Moving into the "orient probe" step changes the view presented to a 2-D ultrasound image, and constrained the vertical motion of the ultrasound probe, allowing the surgeon to slide the probe across the surface, and adjust its orientation, while maintaining constant contact pressure. Movement of the master commanding slave motion normal to the phantom surface plane were ignored. This prevented the surgeon from over compressing the tissue with the probe, and thus distorting the vessel shape.

Once the probe had been placed and oriented correctly, moving into the "position needle" phase locked the position of the ultrasound probe, creating a reliable, fixed image upon which to plan the needle insertion.

Needle insertion planning

For planning the needle insertion, software was created to map between the selected 2D target position on the ultrasound image and the location of that target point in 3D space.

After placing the ultrasound probe and moving the needle to the starting point of the insertion path, the surgeon graphically selected the target point on the ultrasound image by using the hand controller. During this portion of the procedure, only a 2-D ultrasound view with a cross-hair cursor is visible to the surgeon. Hand controller position inputs are ignored and the position of the needle tip is maintained. Rotation of the hand controller simultaneously adjusted both the orientation of the needle, and the position of the displayed cross-hair on the 2-D image. The fixed needle tip position avoids potential damage or accidental penetration of the phantom with the needle during the "blind" manipulation. The displayed cross-hair position was calculated to correspond to the 3-D intersection of the vector defined by the needle orientation and tip coordinate, and the ultrasound image plane.

Once the target point was selected from the 2-D ultrasound, the linear needle insertion distance was calculated. To avoid penetrating ancillary tissue, this needle insertion depth was verified to not exceed a maximum insertion depth. The foot pedal initiated command from the surgeon initiates the needle insertion along the verified path and depth to the target position. A 5-second delay was added to permit cancellation of the insert command, should the surgeon see fit. A trapezoidal velocity profile was used during the linear path move to insure smoothness.

Data

For the NEEMO 12 experiments, the master console was set up in Nashville, Tennessee, and the slave robot was deployed into the Aquarius habitat by the NEEMO 12 crew. The remote image-guided needle insertion was successfully performed multiple times between May 11 and May 13, 2007. The experiments culminated in a successful live demonstration for attendees of the ATA 2007 conference.

During the experiment, a 3Mbps Internet connection was used to connect the master console from the show floor of the ATA conference. On the Haivision encoder, each of the three video streams (left and right stereo camera views, ultrasound) was set to 500 Kbps, and the robot control data used approximately 500 Kbps. During the experiment, network latencies between Nashville and the Aquarius habitat ranged from 60-120 ms.

Problems with technology

Insertion into initialization fixture: For robot initialization and calibration of its encoders, the robot arms must be manually placed into an initialization fixture, which mates with a round metal collar on each robot arm. A locking pin will only insert correctly in one orientation of the robot arm, but there is nothing to prevent the arm from being inserted in another, incorrect orientation. During performance of some of the experiments, it was not apparent that the robot arm had been improperly inserted into the initialization fixture. When the surgeon began to use the robot, the directions of motion were mapped incorrectly. Upon reinitialization with proper arm insertion, the robot worked correctly. To address this potential use error, the initialization fixture and the round metal collar on the robot will modified to an asymmetrical shape that will prevent improper insertion.

Removal from initialization fixture: Upon startup, with direct teleoperation, it is somewhat difficult for the surgeon to move the slave robot arms out of the initialization fixtures, since a slight twisting in orientation can cause interference between the initialization fixture and the mating collar on the robot arm. During conduct of the final experiment, this interference caused the robot arm to become stuck in the initialization fixture, building up tension in the robot cables. The robot was restarted, thus relaxing and then re-tensioning the cables. When the robot began to move, one of the cables slipped off a pulley, and the NEEMO 12 crew was unable to reseat the cable in the confined Aquarius habitat.

Since the NEEMO 12 experiments, the software has been modified to minimize dramatic changes in cable tension on startup. More significantly, autonomous removal of the robot arms from the initialization fixtures has been implemented. This autonomous motion moves the slave robot arms from the initialization fixtures into the surgeon's field of view upon startup. Once the autonomous motion is complete, the surgeon is free to control the robot.

Presentations

A live demonstration of the remote image-guided needle insertion was successfully performed for attendees of the ATA 2007 conference in Nashville, Tennessee on May 13, 2007. The master console in Nashville was used to control the robot deployed in the Aquarius habitat off the coast of Key Largo, Florida.

NEEMO 12 Media Coverage

SRI's participation in NEEMO 12 was covered by a number of media channels:

San Jose Mercury News**:** Robo-MD: Menlo Park's SRI International Designs Surgical Devices for Hospitals, Space, Battlefield

This article about telesurgery focuses on recent advances and milestones in the field. The article describes how NASA will conduct its second test in a year of a robot made by SRI to determine its feasibility for use on a future mission. SRI's Tom Low, director of the medical systems and robotics program, is quoted in the article.

URL: http://www.mercurynews.com/business/ci_5831343

Also See:
Akron Beacon Journal/Ohio.com
http://www.ohio.com/mld/ohio/news/nation/17200212.htm

Contra Costa Times
http://www.contracostatimes.com/business/ci_5844746

Real Cities
http://www.realcities.com/mld/realcities/news/nation/17200212.htm

Red Orbit
http://www.redorbit.com/news/technology/926501/robomd_surgical_devices_for_hospitals_space_battlefield/index.html

***Space Ref.com*:** NASA Space Simulation and Training Project: NEEMO 12

This announcement is a status report from the 12th Mission of NASA Extreme Environment Mission Operations (NEEMO). The announcement describes the crew and experiments that will take place. SRI's surgical robot is noted as one of the telesurgery demonstrations.

URL: http://www.spaceref.com/news/viewsr.html?pid=24106

***USA Today*:** Aquanauts test robotic surgeons in undersea lab

This article is about NASA's Extreme Environment Mission Operations (NEEMO) 12 expedition. The article explains that in the mission, a team of six aquanauts and two robotic surgeons will plunge into the Atlantic Ocean to test new medical and exploration tools for long duration spaceflight. The article notes that SRI's M7 surgical robot will be tested on the NEEMO 12 mission.

URL: http://www.usatoday.com/tech/news/robotics/2007-05-07-robot-undersea-test_N.htm

Also See:

Yahoo! News
http://news.yahoo.com/s/space/20070507/sc_space/deepdivingteamtotestroboticsurgeonsonseafloor

Fox News
http://www.foxnews.com/story/0%2C2933%2C270530%2C00.html

***Robotics Online*:** Robot Surgery: Get the Scoop at the International Robots & Vision Show

This brief article notes that NASA and the military are exploring the use of surgical robots for space missions and combat zones, and that SRI is "providing help." The article links to a recent *SJ Mercury News* article that highlights SRI's role in the NEEMO 12 mission.

URL: http://www.roboticsonline.com/public/articles/articlesdetails.cfm?id=2934

SpaceRef.com: NASA NEEMO 12 Mission Journal Tuesday, May 8, 2007

This is a journal entry regarding NASA's NEEMO 12 mission. A demonstration of SRI's M7 surgical robot is among the upcoming experiments described in the journal.

URL: http://www.spaceref.com/news/viewsr.html?pid=24157

***Tennessean*:** Telemedicine Could Allow Remote Surgery by Robot Someday

This article is about telemedicine breakthroughs on display at the American Telemedicine Association conference in Nashville. The article describes an SRI demonstration where an engineer in the exhibit hall controlled a remote-controlled surgical robot underwater off the Florida Keys. The article includes a photo of Tom Low, director of SRI's medical systems program, performing the demonstration.

URL: http://www.tennessean.com/apps/pbcs.dll/article?AID=/20070515/BUSINESS01/705150333/1003

Also See:
Ashland City Times
URLhttp://www.ashlandcitytimes.com/apps/pbcs.dll/article?AID=/20070515/BUSINESS01/705150333/1436/BUSINESS

Robertson County Times
http://www.rctimes.com/apps/pbcs.dll/article?AID=/20070515/BUSINESS01/705150333/1436/BUSINESS

Fairview Observer
http://www.fairviewobserver.com/apps/pbcs.dll/article?AID=/20070515/BUSINESS01/705150333/1436/BUSINESS

***Space.com*: Undersea NASA Expedition a Success**

This article reports on the successful completion of NASA's NEEMO 12 undersea mission and notes that SRI's "M7 surgical automaton" was studied for future applications in remote areas of the world and on long-duration spaceflights.

URL: http://www.space.com/missionlaunches/070518_neemo12_ends.html

Appendix D

UW BRL Report

The appended report is as it was prepared by UW BRL. It has been formatted to fit this final report.

Evaluation of RAVEN Surgical Telerobot during the NASA Extreme Environment Mission Operations (NEEMO) 12 Mission

University of Washington
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PI – Blake Hannaford, PhD
Contributors:
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Jacob Rosen, PhD
Ganesh Sankaranarayanan

December 14, 2007

Overview

The University of Washington's BioRobotics Laboratory, under the direction of Dr Blake Hannaford, supported the University of Cincinnati's telesurgery effort during the NEEMO 12 mission conducted May 7-18, 2007. The UW RAVEN telerobotic system was deployed to the Aquarius Habitat to conduct a variety of research tasks.

The goals of this mission were to advance and demonstrate technologies related to remote healthcare for astronauts on extended space missions. In particular, the capability of surgical intervention by remotely operated surgical robotics. Two surgical robots were deployed into the Aquarius habitat, the UW RAVEN and the SRI, International M7 robot. Control of the robots was provided over an Internet link from UW (Seattle, WA) and SRI (Palo Alto, CA), respectively. The last 10 mile connection to the remote site was provided by a microwave link from shore to buoy and a 20m cable down to the habitat. Organization for the remote surgery component of the NEEEMO-12 mission is included expertise from Dr. Hannaford, Dr. Jacob Rosen, Mr. Mitch Lum, and Ms. Diane Friedman.

Mission Preparation

Prior to the mission, UC surgeon Dr. Timothy Broderick, NASA flight surgeon Dr, Joseph Schmid, and geologist Mary Sue Bell came to the University of Washington for two days of training. They learned and practiced procedures for operation, assembly and disassembly of RAVEN.

In preparation for integration of the RAVEN into the habitat, NASA requirements necessitated creation of extensive operational documentation for the RAVEN's startup, shutdown, and E-stop recovery procedures. RAVEN was shipped to the NURC operational facility on 23-April-2007. Two UW graduate students, Mitch Lum and Diana Friedman then traveled to NURC and set up RAVEN and verified operation. The RAVEN was then dismantled, packaged and potted down to the Aquarius by U.S. Navy divers. Mr. Lum made a dive down to the habitat to repair some damage to the RAVEN sustained by water pressure applied through the walls of the dive bag.

Drs. Broderick and Schmid reassembled the RAVEN in Aquarius for the teleoperation experiments. (Figure 1) The RAVEN was controlled from three separate locations. Master consoles were set up in Seattle, at the shore base in Key Largo FL, and at Cincinnati Museum Center in Cincinnati, OH. Operators at these locations tested other, non-surgical performances of the robot including simulated manipulation of moon rocks in a sterile environment. All locations used the Sensable Phantom Omnis as the input devices. (Figure 2). Surgeons performed experimental benchmark tests drawn from the Society of American Gastrointestinal Endoscopic Surgeons (SAGES) Fundamentals of Laparoscopic Surgery (FLS) test protocol (Figure 3).

For surgery tasks in Seattle, two different video systems were used (HaiVision to VLC and iChat V.2.1.3 on Apple Macintosh), as explained below. The HaiVision 1060 (HaiVision Systems Inc, Montreal) is a hardware video CODEC providing MPEG- 4 AVC H.264 video compression and decompression. The HaiVision 1060 encoded the video stream, and a laptop PC running VLC media player (http://www.videolan.org/vlc/) displayed the video on the surgeon side. Picture quality was excellent at full laptop screen resolution. However, latency between Seattle and Florida was quite noticeable to users, on the order of one second. Internet round trip latency for the command packets was measured as only 70 ms so the majority of this time was due to video compression and decompression. The HaiVision video parameters for the NEEMO 12 experiment are shown in Table 2. Video picture quality using the HaiVision system is approximated by the screen photo taken during the mission, Figure 4.

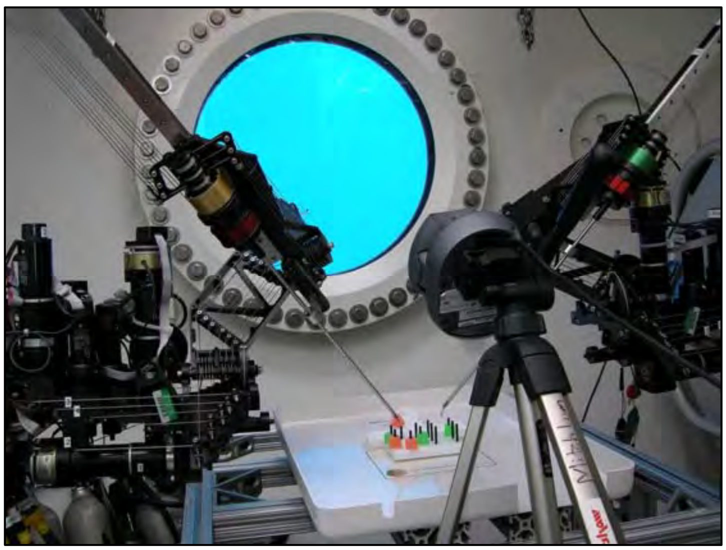


Figure 1. RAVEN robot set up inside the underwater habitat and positioned for experimentation with the laparoscopic training tasks.

Figure 2. Portable surgical workstation as set up at the NEEMO on-shore site showing Phantom Omni hand control devices and video feed from the underwater habitat.

Figure 3. Control station set up at UW during NEEMO mission. Dr. Andrew Wright is operating the robot.

Table 2. Video Parameters for NEEMO-12 Experiment

Parameter	Value
Encapsulation	H.264
Video Input	S-Video
GOP	30
Framing Mode	IP
Interlacing	MBAFF
Resolution	Full D1 (720x480)
Video Bit Rate	1-1.5 Mbps

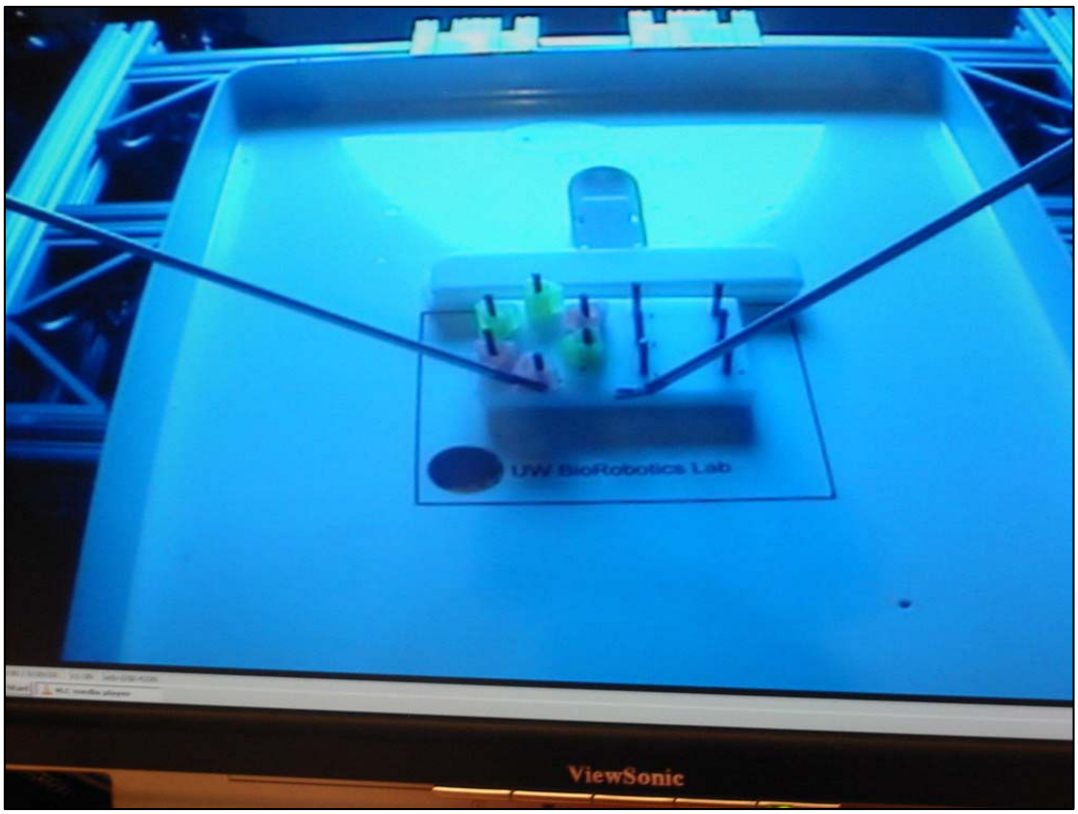


Figure 4. Screen shot taken during the NEEMO experiment showing video quality obtainable. This photo was taken from the Viewsonic LCD monitor. Color balance has not been measured or corrected.

RAVEN Surgical Robot Mechanism and Control

The 7-DOF surgical manipulator used force/torque data collected by the Blue Dragon, the preliminary experimental evaluation and the kinematic optimization as a foundation for its design. The robot is divided into three main subsystems: the static base that holds all seven actuators, the spherical mechanism that positions the tool, and the tool interface. The motion axes of the surgical robot are:

1. Shoulder Joint (rotational)
2. Elbow Joint (rotational)
3. Tool Insertion / Retraction (linear)
4. Tool Roll (rotational)
5. Tool Grasping (rotational)
6. Tool Wrist1 Actuation (rotational)
7. Tool Wrist2 Actuation (rotational)

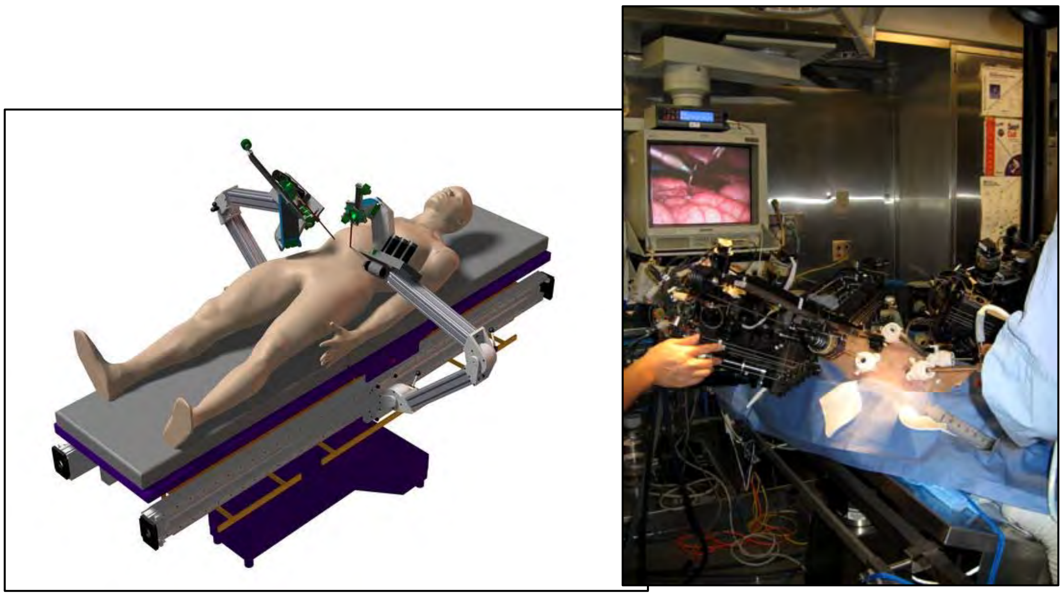


Figure 5. RAVEN CAD model and RAVEN during animal experiment.

The first four joint axes intersect at the surgical port location, creating a spherical mechanism that allows for tool manipulation similar to manual laparoscopy. Brushless motors mounted to the base of the micromanipulator actuate all motion axes. The motors are mounted on quick-release plates, which allows for motor removal without the need for disassembling the cable system. Maxon EC-40 motors with 12:1 planetary gearboxes are used for the first three axes, subject to the highest torques. Maxon EC-32 motors are used for the remaining axes. Maxon DES70/10 series amplifiers drive the motors.

The selection of DC brushless motors over brushed motors was motivated by a better torque to weight ratio as well as more efficient heat dissipation due to the fact that the motor's windings are thermally coupled to its outer case. While the performance benefits of brushless motors are clear, they required more complex and expensive controllers and extensive wiring (14 conductors per motor). The motors of the first three axes have power-off brakes to prevent tool motion in the event of a power failure.

The cable system is comprised of a capstan on each motor, a pretension adjustment pulley, a pulley array to redirect the cables through the links, and attachment to each motion axis. The shoulder axis is terminated on a single partial pulley. The elbow axis has a dual-capstan reduction stage terminating on a partial pulley; the tool insertion / retraction axis has direct terminations of the cables on the tool holder. The tool rotation, grasping and wrist cables are terminated on capstans on the tool interface box.

Each axis is controlled by two cables, one for motion in each direction, and these two cables are pre-tensioned against each other. The cables are each terminated at both ends, to prevent any possibility of slipping. The cable system maintains constant pretension on the cables through the entire range of motion; however, there are force and motion couplings between the axes, which must be accommodated for in the control system.

The mechanism's links are machined from aluminum, and are generally I-section shapes with structural covers. These removable covers allow for access to the cable system, while improving torsional stiffness of the links when they are in place. The links are also offset from the joint axis planes, allowing for a tighter minimum closing angle of the elbow joint. Laser pointers attached the shoulder and elbow joints allow for visual alignment of the manipulator relative to the surgical port. When the two dots projected on the skin of the patient converge, the manipulator is positioned such that the center of rotation of the surgical manipulator is aligned with the pivot point on the abdominal wall.

Each surgical manipulator has a mass of approximately 15 kg, which includes the motors, gear heads and brakes.

Tool Interface:

The tool interface (Figure 6) allows for quick changing of tools and controls the tool rotation, grasp and wrist axes. A robotic tool changer can release the tool from and attach the tool to the mechanism with a single grasping motion. The tool tips used are modified micro-wrist tools from the Computer Motion’s Zeus platform. The tools' grasp and wrist axes are actuated by pushrods in the tool shaft. High pitch threads are used to convert the rotational motion of the cable system capstans into linear motion of the tool pushrods.

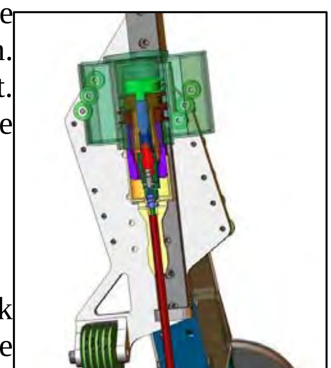
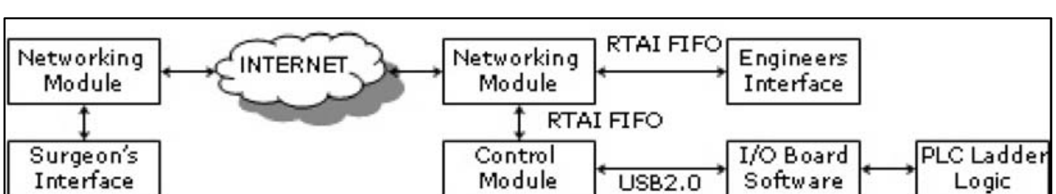


Figure 6. Tool interface allows rapid change of surgical tools

We developed a USB 2.0 interface board that serves as the data link between the control software (running on a RTAI Linux computer) and the motor controllers. The USB board includes eight channels of 16bit digital to analog converters for control signal output to each motor controller and four dual channel 24bit quadrature encoder readers. The board can perform a read/write cycle in 125ms.

The overall architecture is very modular to facilitate future development and expansion or collaboration with other groups. The master (Surgeon Console) and slave (Surgical Manipulators) communicate through a Networking Module. Thus, the Surgeon Console



could be any piece of software with supporting hardware to communicate with the slave. Figure 7 illustrates the overall software architecture of the Surgical Robot System.

Figure 7. Control System Architecture

When surgeons transitioned from open surgery to MIS, their sense of touch was greatly diminished. Friction between the surgical tool and the seal of the MIS port, as well as the forces exerted on the port by the abdominal wall greatly reduce the surgeons' ability to feel the tissue they interact with. With the right master interface device, surgical robots present an opportunity for surgeons to regain and potentially enhance their sense of touch in MIS procedures. One of the design goals was to develop a lightweight, low inertia and back-drivable mechanism suitable for enabling force-feedback capabilities in bilateral teleoperation.

Currently, the Phantom Omni (SenseAble Technologies) is used as the master device. The Phantom line of SenseAble haptic devices is well established among haptics researchers. The cost-effective Omni provides a straightforward software interface that allowed rapid implementation of a surgeon interface device into a master/slave system. It features 3-DOF force-feedback and 6-DOF position/orientation sensors. Additionally, the surgeon station includes a position indexing foot-pedal that enables and disables the surgical manipulator, allowing the surgeon to put down the Omni styluses without moving the robots.

Software and Safety Architecture:

The control system and supported electronic hardware were designed to incorporate safety, intelligence, modular design, and flexibility. As this is a medical device, the most critical of these aspects is safety. Inherent to a safe system is robustness, reliability, and some level of automatic override. Our system includes safety features such as: a small number of states, Programmable Logic Controller (PLC) state transition control (Figure 8), active enable, power-off brakes, E-STOP, and a surgeon foot pedal. With these features we have a system that we expect will provide a level of predictability, reliability, and robustness sufficient for animal surgery evaluation.

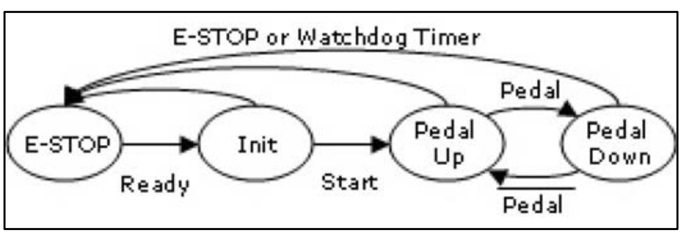


Figure 8. Control System State Diagram.

A programmable logic controller (PLC - Direct Logic 05) controls the system state transitions based on inputs received from the system and generates outputs to control the RTAI software state, the motor-enable and brakes. PLCs are a well-developed technology used extensively in automation applications. PLC technology is assumed to be inherently reliable, providing built-in safety circuitry that is easy to use. In addition to monitoring the system hardware, the PLC monitors the health of the control software through the use of a watchdog timer. The watchdog timer monitors a square-wave signal from the control software. This square-wave may be considered the “heartbeat” of the control software. In the event of a software failure, the PLC will detect the loss of the heartbeat signal and immediately switch the system into the Emergency Stop state, enabling the brakes and disabling the motors. An array of status LEDs display the current state of the system.

Engineers' Interface

Robot development is assisted by the Engineering Interface (EI); a low-level interface to the system states and control software. Developers are presented with an intuitive GUI with easy access to the robot's features. In development stages, the system state - stop, init, run, e-stop – can be set manually with the click of a button. Control commands can be sent to any degree of freedom or the entire robot; for example, a 40 degree sine wave can be commanded to the shoulder joint, motor controller number two can output 30% maximum current, or endpoint position can be instructed to move 3cm to the left. Furthermore, robot states (i.e. motor output, joint position, end-effector position) are output on-screen in real-time, and also logged for later evaluation.

The EI can connect to the RTAI Linux control system by two FIFO device nodes or a single, bi-directional (TCP/IP) network socket. Two types of data are exchanged: (1) a packet containing all robot-state information is received by the EI, and (2) a command packet with all instruction parameters is sent from the EI to the control software. This link is independent of the master-slave link. A touch-screen based surgeon interface has also been developed.

Research Findings

Publications

The following publications describing some of our NEEMO results have been published or will soon appear:

- Mitchell J.H. Lum, Diana C.W. Friedman, Hawkeye King, Ganesh Sankaranarayanan, Jacob Rosen, Timothy J. Broderick, Mika N. Sinanan, Blake Hannaford, "Raven – A Surgical Robot for Teleoperation", Submitted, American Telemedicine Association Conference, Seattle, April 2006.
- M. Lum, et al., “Objective Assessment of TeleSurgical Robot Systems: Telerobotic FLS,” In-Press, proceedings of MMVR 2008, Long Beach, CA, January 2008.
- G. Sankaranarayanan, L. Potter, B. Hannaford, 'Measurement and Simulation of Time Varying Packet Delay with Applications to Networked Haptic Virtual Environments,' Proceedings of Robocom 2007, Athens, Greece, October 2007.
- G. Sankaranarayanan, H. King, S.Y. Ko, M.J.H. Lum, D. Friedman, J. Rosen, B. Hannaford, 'Portable Surgery Master Station for Mobile Robotic Telesurgery', Proceedings of Robocom 2007, Athens, Greece, October 2007.

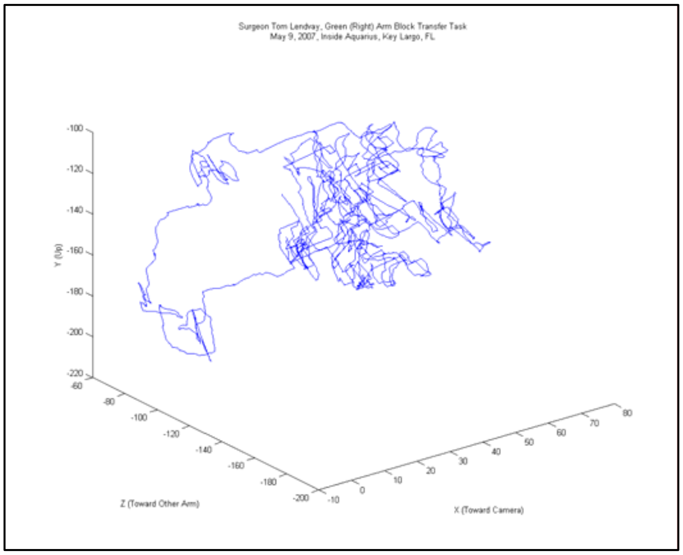


Figure 9. 3D tracing of performance of the FLS block transfer task by surgeon Thomas Lendvay by remote control between the University of Washington, Seattle, and the RAVEN robot situated in Aquarius.

Robot Motion Data Recordings

Our computers collected about 6.8Gb of motion data including position velocity, and torque for both RAVEN manipulators recorded at 100Hz for all operations in Aquarius and NURC. This data is still being analyzed. A sample of the data is reproduced in Figure 9. In this sample, the surgeon is moving the blocks up and down on the pegs of the FLS task board.

Network Data Performance Data

One of our goals in the NEEMO-12 mission was characterization of the network quality between the control site at UW in Seattle and the Aquarius habitat. This delay was composed of two components: 1) The regular Internet between UW and NURC and 2) the special microwave link between NURC and Aquarius. These links were characterized in terms of round trip time delay. Our computers inside RAVEN contained a packet reflector program. Another program at UW sent regular streams of test packets to the packet reflector and measured round-trip delay time for each packet. Although similar to the standard ping command measurement, this system used UDP packets of the same type used in teleoperation.

Results

Measured delay distributions are shown in Figure 10. The mean and standard deviation were 76.5ms and 5.4ms respectively. When packet sending rates were decreased from 1000Hz to 10 Hz these statistics were essentially unchanged.

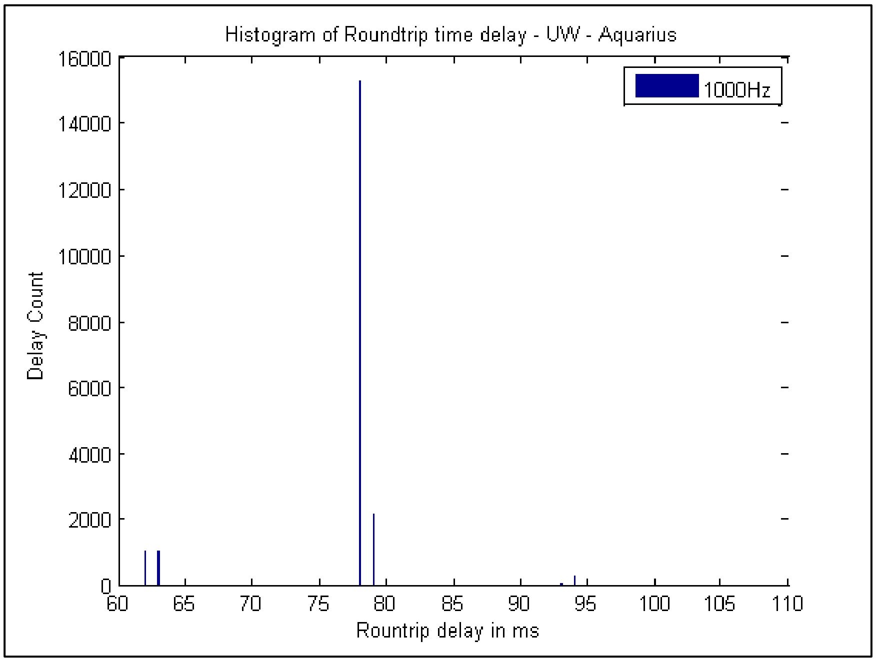


Figure 10. Distribution of round trip time delays for packets between UW and the Aquarius habitat taken during NEEMO-12. Delay distribution was quite similar for 100 Hz and 10 Hz packet repetition rates.

Another parameter of Internet packet timing is the correlation coefficient of the time delays of adjacent packets. This is a measure of network congestion which ranges from 0-1.0. If the correlation is close to one, routers are queueing packets as they must wait for links. Packet delay correlation was essentially zero (indicating low congestion for 10 – 100 Hz, and rose to 0.135 for 500Hz. The only significant amount of congestion was observed at 1000Hz were the correlation coefficient was 0.51. Although packet latency was not affected as rate was increased to 1,000Hz, the growing correlation coefficient suggests that the network was near its bandwidth limit.

Tests from UW to the NURC alone (i.e. not using the microwave link for the last 5 miles) gave a mean delay of 75.2ms and standard deviation of 6.3ms. Thus the microwave link to the Aquarius was highly efficient and not a network bottleneck.

Conclusion

The RAVEN was successfully deployed and demonstrated in the habitat. Surgeons and researchers were able to operate the robotic arms using the controllers linked across several thousand miles. This included the ATA exhibit in Nashville and the CMC in Cincinnati, OH.